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Vibrating Systems with Limited Power Supply: An Emergent Topic after Prof. Kononenko

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Abstract
We analyzed the dynamical coupling between energy sources and structural response that must not be ignored in real engineering problems, since real motors have limited output power. Recent and old studies in the Non-ideal vibrating systems main properties have been reviewed. Several interesting phenomena were presented and studies of the corresponding vibrating systems are leading to advances in their comprehension. In this paper, an overview on non-ideal vibrations is presented. We analyzed the physical phenomena involved; the adequate methodologies to deal with them and presented a report of some recent progress, in the period from 1969 to 2016, published over the current literature in honor of in honor to Prof. Kononenko's from Ukraine.

Keywords
Limited Power Supply, Non-ideal Vibrations, Energy transfer, Sommerfeld Effect, Saturation phenomenon.

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Introduction

The highly generic, interdisciplinary quality of the insights gained in the last few decades has spawned myriad applications in almost all branches of science and technology and even well beyond. Wherever the quantitative modeling and analysis of complex, nonlinear phenomena are required, chaos theory and its methods can play a key role. Its include systems.

Chaos and nonlinear dynamics initially developed as a new emergent field with its foundation in engineering and applied sciences. Analytically modeled, numerically simulated, and experimentally realized to demonstrate enhanced capabilities and new challenges.

By considering that most realistic vibration environments are more accurately described as either stochastic, multi-frequency, time varying, or some combination thereof, narrowband linear systems are fated to be highly inefficient under these conditions.

Nonlinear systems are capable of responding over a broad frequency range; suggesting an intrinsic suitability for efficient performance in realistic vibration environments. The study of problems involving of the coupling of several systems was widely explored, in the last years, essentially in function of the change of constructive characteristics of the machines and structures.

Accordingly, oscillatory processes can be divided into the following types: free, forced, parametric and self-excited oscillations and we remarked that two or more oscillations can interact in the same oscillatory system. This fact is of important scientific and practical interest.

In this way, some phenomena were observed in a composed dynamic systems supporting structures and rotating machines, where were verified that the unbalancing of the rotating parts, was the greatest causer of the vibrations.

The research on non-ideal vibrating systems, that is, when the excitation is influenced by the response of the system, has been considered a major challenge in theoretical and practical engineering research. When the excitation is not influenced by the response, it is said to be an ideal excitation or an ideal source of energy. On the other hand, when the excitation is influenced by the response of the system, it is said to be non-ideal. Then, depending of the excitation, one refers to vibrating systems as ideal or non-ideal. The behavior of the ideal vibrating systems is well known in the current literature, but there are few results on non-ideal ones.

Generally, Non-ideal vibrating systems are that for which the power supplies is limited. The behavior of the vibrating systems departs from the ideal case, as power supply becomes more limited. For Non-ideal dynamical systems, one must add an equation that describes how the energy source “supplies the energy to the equations” that governs the corresponding ideal dynamical systems and the response is unknown.

We remarked that the problem of passage through resonance of unbalanced equipment, with an operational speed higher than the lower frequencies of vibration of the supporting structure has been studied for a long time. However, the machine may not be able to supply the power necessary for this technique, as a large part of its energy is used in shaking the structure and not in accelerating the rotation of the shaft. This is the *Sommerfeld effect*.

Note that as long as the rotation of the motor is assumed to be uncoupled from the vibrations excited upon the supporting structure, one has a known forcing function of time, corresponding to an unlimited or ideal power supply. The introduction of real torque–speed curves for non-ideal motors renders the system nonlinear and capable of multiple steady-state periodic motions whose stability must be assessed. Further complexities may be introduced if the structure itself exhibits nonlinear behavior.

Here, recent and old studies in the non-ideal vibrating systems main properties have been reviewed. Several interesting phenomena were presented and studies of the corresponding vibrating systems are leading to advances in their comprehension. We presented models of certain problems that render descriptions that are closer to real situations encountered in practice.

Jump phenomena and the increase in power required by a source operating near resonance are manifestation of a non-ideal energy source and they are often referred as the Sommerfeld effect. These phenomena suggest that the vibrational responses provide an energy sink, and thus we pay to vibrate the structure rather than to operate the machinery. One of the problems often faced by designers is how to drive a system through resonance and avoid this kind of energy sink.

This paper aims to deals with the most relevant contemporary applications of nonlinear and chaotic vibrating systems as they apply to the various cutting-edge branches of engineering and science, mainly in non-ideal systems, *in honor to Prof. Kononenko's from Ukraine*.

For complete and comprehensive details and different approaches of this kind of problem, see: for a complete review of different approaches in references mentioned in [1-16], without undeserved of others. By other hand, new approaches to the classical non-ideal researches were done, with success, through a number of new publications, in last years.

The goal of this paper is to present them, in a systematic way, bringing them together and developing some specific points.

1. Modelling And Governing Equations of Motion of Non-Ideal System

The non-ideal (abbreviated by (**NIS**)) mathematical model of a vibrating system can be characterized by its governing equations of motion

$$\begin{aligned} m_1\ddot{x} + f(x,\dot{x}) + \frac{\partial U(x)}{\partial x} &= F(\varphi,\dot{\varphi},r,m_0) \\ I\ddot{\varphi} + H(\dot{\varphi}) &= L(\dot{\varphi}) + R(\varphi,\dot{\varphi},\ddot{x},r,m_0) \end{aligned} \qquad (1)$$

where m_1 is the mass, x is displacement of the (**NIS**), φ is angular displacement of the rotor, $F(\varphi,\dot{\varphi},\ddot{x},r)$ expresses the action of the source of energy on the oscillating system (angular velocity of motor, that is not constant), parameters e and m are the eccentricity and mass of unbalanced shaft of the electric motor, I is the moment of inertia of the rotor, the function $R(\varphi,\dot{\varphi},\ddot{x},r)$ expresses the action of the oscillating system on the source of energy, the function $H(\dot{\varphi})$ is the resistive torque applied to the motor, the function $L(\dot{\varphi})$ is the driving torque of the source of energy (motor). Note that, usually, the inductance is much smaller than the mechanical constant time of the system and, then in stationary regime, we can take $L(\dot{\varphi})$ as (linear) : $L = a - b\dot{\varphi}$, where are a related to voltage applied across to the armature of the DC motor, that is, a possible control parameter of the problem and b is a constant for each model of DC motor considered. $f(x,\dot{x})$ Is the nonlinear and non-conservative part of the restoring force, while $\frac{\partial U(x)}{\partial x}$ is its conservative part(U is the potential, or strain energy).Fig 1 shows the (ideal system abbreviated by(IS))and (NIS: that is non-ideal system) possible schematics.

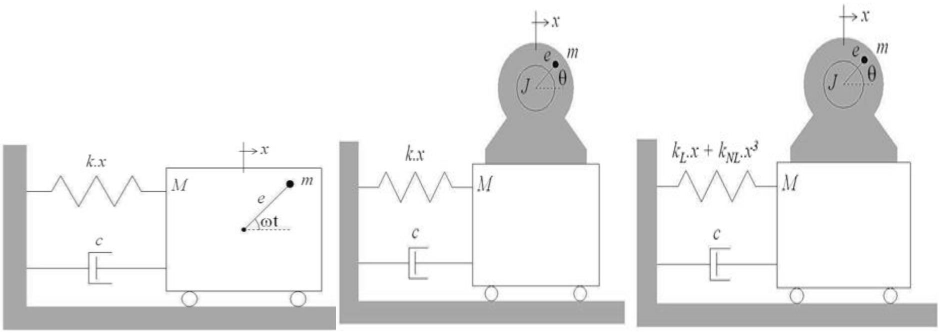

Figure 1. a- (IS), b- linear (NIS), c- (NIS) schematics**.**

The governing equations of motion for (IS) –a

$$\ddot{x} = -\frac{c}{(M+m)}\dot{x} - \frac{k}{(M+m)}x + \frac{m.e.\omega^2}{(M+m)}.\cos\omega t \tag{2}$$

And to (NIS)-c is:

$$\begin{aligned} \ddot{x} &= -\frac{c}{M+m}\dot{x} - \frac{k_L}{M+m}x - \frac{K_{NL}}{M+m} - \frac{me}{M+m}(\dot{\theta}^2\cos\theta + \ddot{\theta}\sin\theta) \\ \ddot{\theta} &= \frac{a}{I_{sist}} - \frac{b}{I_{sist}}\dot{\theta} + \frac{me}{I_{sist}}(\ddot{x}\sin\theta - g\cos\theta) \end{aligned} \tag{3}$$

According to [5].in case of (IS), the curve of response in frequency, with a rotating unbalance it is observed that the amplitude of vibration occurs when the excitation frequency coincides with the natural frequency of the system. The response is always periodic. In the case of (NIS) the curve of response in frequency shows a jump (discontinuity), known as *Sommerfeld effect*.

In this system it is also perceived the capture effect by resonance condition in which the power supplied to the electric motor causes a small increase in its rotation and a large increase in the amplitude of the vibration system.

In the case of non-linear (NIS), the dynamic behavior becomes quite complex because of the nonlinear stiffness with elastic potential energy with two potential wells. Small variations in motor frequency cause major changes in the system response.

For this system the response is periodic or chaotic depending on the motor frequency constant value. This referenced interaction is related to existence of quasi-period solutions [5]. If the support(NIS) foundation(Eq. 1a) has two degree of freedom as the possibility of occurrence of saturation of high frequency low amplitude mode and transference of energy to low frequency high amplitude mode[3].

By considering the external exciting current I_m, the dynamic behavior it is significant, particularly for regions where chaotic motion it is possible[5] and considering some values of the fractional damping parameter, it were obtained different responses as regard the fractional (NIS)[4].

1.1 Recent Developments on (NIS) mathematical models ("*upgrades*")

Taking into account that in a vibrating system, with small low viscous dissipation, the energy initially imparted to the primary sub-system, may be transferred to the *nonlinear energy sink*(abbreviated by (**NES**))-([17]) reducing the amplitudes of vibrations of the (**NIS**) and eliminating (or reducing) the occurrence of the S*ommerfeld effect*, both inside and outside resonance region, respectively. In this particular case, we will need to consider more one equation in Eel (1) ([18])

$$m_2\ddot{y}+c_2\dot{y}+g(y)+\frac{\partial V(x,y)}{\partial y}=0 \tag{4}$$

where m_2 is the mass, c_2 is the coefficient of the viscous damping and y is the displacement of the (NES), $g(y)$ is the stiffness term not necessarily linear of the (NES), V is the potential energy not necessarily linear associated with the coupling spring.

By other hand, the effectiveness of a nonlinear electromechanical vibration absorber (abbreviated by (**NEVA**)), in the vibration attenuation of a (**NIS**) was done by [18-20]. They, have dealt with the study of a (NIS), coupled to a nonlinear electromechanical vibration absorber. They considered a nonlinear friction of type cubic-quantic Duffing oscillator and by considering the voltage of the resistor as being a nonlinear function of type Rayleigh oscillator.

We observed that the passage of the resonance region, a dramatic decreasing of the vibration amplitude of the (**NIS**) and to with the possibility of the minimization of the Sommerfeld effect of (NIS). They taking into account that the electric part of the controller was consisted of a linear inductor L, a nonlinear capacitor C, and nonlinear resistor R and the expression of the voltage over the resistor and the condenser were a nonlinear function of the instantaneous electrical charge q .We need to consider more one equation in Eq (1):

$$L\ddot{q}-R\left(1-\frac{1}{i_0^2}\dot{q}^2\right)\dot{q}+\frac{1}{C_p}q+i_0^2\alpha_a q^3+i_0^4\alpha_b q^5+T\dot{x}=0 \tag{5}$$

Where i_0 is an initial current, in the electrical part, C_0 is the linear value of the capacitive characteristic and the parameters α_3 and α_5 , are a nonlinear coefficients, those depending on the type (or kind) of the capacitor. The quantity T is the transducer (constant), which relates the current in the coil to the magnetic force on the considered coil. The transducer constant is given by $T=2\pi nlB$, where n is the number of turns in the coil, l is the radius of the coil, and B is the uniform radial magnetic field strength in the annular gap. The transducer constant T also relates the electrical potential e, across to the terminals of the coil to the velocity of the coil, with respect to the permanent magnet. It is important to note that the Eq (1), must be replaced by

$$m_1\ddot{x}+f(x,\dot{x})+\frac{\partial U(x)}{\partial x}+T\dot{q}=F \tag{6}$$

In the paper by [18], the attenuation of a (NIS) vibrating system, using (NEVA) and magnetorheological damper (abbreviated by (MR) damper) has been presented. The novelty of the (MR) damper application, in this study, was the performance of attenuating the interaction between (NEVA) and (NIS), in the post-resonance region.

The following phenomenon was eliminated: *Sommerfeld effect* and transient motion of long time. The most important results of this paper may be expressed as: in the (NIS), without (NEVA) and (MR) damping, the *Sommerfeld effect* ("Energy Transfer" the strong interaction between the foundation and the DC motor); the influence of the viscous damping; the jump and transient motion, during a long period of time were found.

The authors analyzed the influence of (NEVA) on (NIS), in the post-resonant region, which causes, on a large band in the resonance curve, a set of jumps, two maxima's resulting in a strong interaction, between the (NIS) and (NEVA), and a big jump due to a transient motion, during a long period of time. They also analyzed the influence of the parameters: the magnetic coupling and the nonlinear capacitor for the effective action of (NEVA).

In [19] the authors investigated the nonlinear dynamic behavior of an electro-mechanical vibration absorber (NEVA), taking into account a modified (MR) and (MRD). We also remarked that in its mathematical model, which was excited by a (NIS), by using a perturbation analysis and numerical simulations and in [20] suppressing of chaos in a (NIS) Double-Well Oscillator, using an electromechanical damped device.

2. Some Emergent areas OF NON-ideal Systems (NIS)

It is known that the interactions between the energy source to existence of quasi-period solutions [5], then new applications "borned" in the current literature, using electro-mechanical shaker than D.C. motors .

In recent years a large amount of research has been dedicated to new materials and their use in new structural components. Among new materials, piezoelectric, shape memory alloys, magneto rheological materials, including new types of nonlinearities and forces have shown great potential for applications in all engineering fields.

Nowadays, Fractional stiffness and damping is appearing in different contexts in any systems and (NIS), with memory and hysteresis. Such damping is defined by a fractional derivative in contrary to classical viscous damping term with the first order derivative. As *the memory of* the dynamical system induces extra degree of freedom for the phase space the standard methods of dynamical response analysis and system identification, which relies on the knowledge of system dimensionality cannot be used[4].

2.1 Recent Developments on (NIS) mathematical models ("*upgrades*")

The investigations over the dynamic interaction, between a micro-machined rate gyroscope and variable force actuators, was done using a modelling of a Duffing oscillator, under electrostatic effects, with variable capacitor was done by [21].

The authors, considered the simplified and modified mechanical model for the Microelectromechanical systems(abbreviated by (MEMS)), with variable capacitor, extended earlier results and investigated the dynamic interaction between a micro-machined rate gyroscope and variable force actuators and .developed a linear optimal control design for reducing the oscillatory movement of the nonlinear systems to a stable point. *This is a first result on a series of them on (NIS) micro gyroscope in the literature*, according to author knowledge.

By other hand, in [22] the authors analyzed a proposed mathematical model, by using numerical integrations, taking into account the reciprocal influence between the vertically excitation, due an electro-dynamical shaker (abbreviated by (EDS)) and the vibration response of a tuning fork beam (abbreviated by (TFB)).The internal physical components of a shaker consist of an electric component coupled magnetically to a mechanical structural one.

Here, the investigation was based the behavior for the macro system. The (TFB) is modeled by two inverted pendulums of motion in the opposite directions hung by the same rods of vertical and horizontal motion.Recently, the researcher in [23] investigate the interaction of the dynamics of the electro-shaker with the gyroscope, demonstrated that under certain parameters the system can exhibit complex dynamic behavior such as chaotic motion.

We also mention that in [24]. In this paper the dynamical interactions of a double pendulum arm and an electromechanical shaker is investigated. The double pendulum is a three degree of freedom system coupled to an electrical circuit consisting of a resistor (R), an inductor (L), and a capacitor (C circuit(abbreviated by (RLC))circuit based nonlinear shaker through a magnetic field, and the capacitor voltage is a nonlinear function of the instantaneous electric charge. Numerical simulations show the existence of chaotic behavior for some regions in the parameter space and this behavior is characterized by power spectral density and Lyapunov exponents. The bifurcation diagram is constructed to explore the qualitative behavior of the system. This kind of electromechanical system is frequently found in robotic systems, and in order to suppress the chaotic motion, the State-Dependent Riccati Equation (abbreviated by (SDRE)) control and the Nonlinear Saturation control ((abbreviated by (NSC)) techniques are analyzed. The robustness of these two controllers is tested by a sensitivity analysis to parametric uncertainties.

Recently, much interest has been demonstrated in the concepts of electro-mechanical systems that are able to scavenge or harvest energy from their operating environment. In the process of energy harvesting, the electrical energy is obtained through of conversion of mechanical energy from an ambient vibration source by a type of transductor, as a piezoceramic thin film, which is a material with piezoelectric properties.

As an example, we mention that in [25] it was presented the extraction of energy from a simple portal frame structure excited via its second (first symmetric) mode. As 2:1 internal resonance is present between that mode and the first (sway) mode, the phenomenon of mode saturation and energy exchange (modal coupling) occurs. Energy pumped into the system through the second (vertical) mode was partially transferred to the horizontal (sway) mode. An evaluation of the energy available for harvesting in each of the considered modes was computed.

Here, the nonlinearities present in the piezoelectric material were considered in the piezoelectric coupling mathematical model.

The dynamical response of systems with shape memory alloy (abbreviated by (SMA)) presents a different behavior due to their nonlinear characteristic. SMA nonlinear response is associated with adaptive dissipation related to their hysteretic behavior. In [26] the authors discuss the nonlinear responses of shape-memory (NIS) oscillators, based on a thermomechanical consistent model with four state variables. Two cases were investigating, namely, the case when (SMA) presents a large hysteresis loop and another one with less hysteresis. Computer simulations were carried out via a numerical approach showing qualitative results concerned with regular and non-regular motions.

Finally, we mention that, by using the Averaging Method the authors in [27] was proved, for the first time, the existence of Neimark-Sacker Bifurcation in a class of Non Ideal mechanical systems (NIS), maybe one more direction to designers to drive an vibrating system through resonance and avoid this kind of energy sink

Conclusions

Recent and old studies in the Non-ideal vibrating systems main properties have been reviewed. Several interesting phenomena were presented and studies of the corresponding vibrating systems are leading to advances in their comprehension.

Here, we presented models of certain problems that render descriptions that are closer to real situations encountered in practice. Jump phenomena and the increase in power required by a source operating near resonance are manifestation of a Non-ideal energy source and they are often referred as the Sommerfeld effect. These phenomena suggest that the vibrational responses provide an energy sink, and thus we pay to vibrate the structure rather than to operate the machinery.

Future works will consider control strategies in order to overcome the main problems appoint here as well an investigation of the dynamics, including of chaos, periodic motions, multiperiodic and quasiperiodic motions and an analysis of basins of attraction, considering the dynamical integrity

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